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Neutrinos from AGN

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Abstract.

The great penetrating power of neutrinos makes them ideal probe of astrophysical sites and conditions inaccessible to other forms of radiation. These are the centers of stars (collapsing or not) and the centers of Active Galactic Nuclei (AGN). It has been suggested that AGN presented a very promising source of high energy neutrinos, possibly detectable by underwater neutrino detectors. This paper reviews the evolution of ideas concerning the emission of neutrinos from AGN in view of the more recent developments in gamma-ray astronomy and their implications for the neutrino emission from these class of objects.

I INTRODUCTION

The probes of the physics and the conditions of the various astrophysical sources and sites requires instruments appropriate for each case. Thus astrophysical objects are observed at a host of wavelengths from radio to gamma rays because observations at each wavelength reveal a particular aspect of emission of the corresponding source. Clearly the choice of each wavelength probes regions at which the corresponding radiation has optical depth at most a few. Different wavelengths therefore, in addition to probing different mechanisms of emission and physical conditions, they also probe different "sizes" of the corresponding sources. This immediately raises the question on whether one can say anything about the conditions which prevail in environments opaque to radiation transport. The radiation emitted at such sites is apparently not accessible to us until after its severe reprocessing and thermalization, which then provides information only about the conditions near optical depth unity.

This end can be achieved by observations of radiation other than electromagnetic through which one can indeed obtain glimpses of these forbidding environments. This is the general idea behind neutrino astronomy. Neutrinos are much more weakly interacting than photons and as such they have no difficulty escaping from environments as dense as those of stellar interiors or even those of neutron stars. Clearly the weaker an interaction is the greater the column density of matter it can penetrate through and the more opaque the source it can provide information

about. Thus, the weakest of interactions, gravity, can probe conditions even more extreme than those probed by neutrinos. The downside of course is that the weaker the interaction the harder it is to produce and the larger and more expensive the detector necessary to detect the associated radiation.

There are astrophysical sites at which neutrinos are known to be produced. These are the centers of stars where the weak interaction gives rise to neutrino production at rates which, for the given star type, can be calculated from the detailed nuclear reactions necessary to maintain hydrostatic equilibrium. Neutrino fluxes from main sequence (or red giant) stars other than the Sun are too low to be detected on the earth. However, during the collapse of stellar cores which have exhausted their nuclear fuel to form supernovae, approximately 10% of a solar rest mass, or 10^{53} ergs, is emitted in neutrinos, the only species that can escape that dense environment over the relevant time scales (and at the same time help produce the explosion). The neutrino flux of such an event is sufficiently high that it is detectable to a distance of several hundreds of kiloparsecs.

Neutrinos from the Sun and a supernova have indeed been observed. This supernova event was that of SN 1987a, which was detected by the IMB underground detector, employed to detect proton decay. Solar neutrinos are best known for the deficit of their observed flux from that expected on the basis of the standard solar model. Presumably this deficit is due to oscillations of electron neutrinos to muon ones which are harder to detect (for a review of all these and more issues see [1]).

The increase of the neutrino cross section with energy has raised the possibility of additional classes of astrophysical objects as potentially detectable neutrino sources by detectors which could be constructed at a reasonable price. The potential sources of high energy neutrino radiation were identified by the requirement of sufficiently large power output, in combination with the possibility of neutrino emission at sufficiently high energy. The latter demand was imposed by the need to overcome the neutrino background due to cosmic ray interactions in the atmosphere. These constraints led to the consideration of Active Galactic Nuclei (AGN) as a potential source of high energy neutrinos.

II NEUTRINOS AND THE PHYSICS OF AGN

The emission and the detection of high energy neutrinos from AGN rests solely on the premise of the presence of relativistic protons of sufficiently high energy and energy density in the AGN central engine. Because a direct consequence of the presence of these relativistic protons is also the production of γ -rays of energies similar to those of neutrinos, high energy neutrino and γ -ray astronomy are closely related. However, while γ -ray photons can be produced even in the absence of relativistic protons, e.g. by a population of high energy electrons, this is not the case with neutrinos. Thus, the detection or not of neutrino radiation from AGN can provide unique information about the workings of their central engines. Also, because photons of energies $E_\gamma \gg 1$ MeV within the AGN engine would be absorbed

and reprocessed to lower energies, neutrinos provide the only window that allows one to search for the presence of high energy processes in this environment.

The γ -ray photons produced near the compact object in an AGN are not expected to be directly observable but absorbed and reprocessed to lower energies; they should nonetheless leave imprints of their presence in the AGN lower energy γ -ray spectra which could then be used to infer the potential for high energy neutrino emission from the specific object. Because γ -ray observations underwent a revolution with the launch of the Compton Gamma Ray Observatory (CGRO), it is natural to distinguish two periods in the AGN neutrino emission models: Those prior to the CGRO launch and those following it.

1 Pre-CGRO Models

The suggestion that high energy (\gtrsim TeV) neutrinos may be a potentially detectable component of the AGN emission came up with the first considerations for the DUMAND neutrino detector [2]. At the time this suggestion seemed not much more than an indication of our ignorance of the physics of AGN. Then, Ramaty & Lingenfelter [3] pointed out that the observed spectra of NGC 4151, Cen A and 3C 273 are roughly “flat” when plotted in energy per logarithmic decade, indicating that all frequencies radiate away roughly the same luminosity, out to energies $E_\gamma \sim 500$ MeV for 3C 273, ~ 1 MeV for NGC 4151 and possibly 300 GeV for Cen A. This suggested strongly that their spectra are indeed non-thermal and that \sim multi-GeV particles contribute significantly to the pressure in these objects. If the entire AGN emission were indeed non-thermal, then the issue of the component which provides the dominant pressure contribution is of fundamental importance in understanding the physics of AGN; the significance of neutrinos lies in that they provide the only means for answering this question.

Motivated by this observation, Protheroe & Kazanas [4] suggested that all AGN emission is non-thermal and that it is produced by the interaction of an accelerated proton component with the ambient accreting gas. Assuming a proton spectrum proportional to E^{-2} (i.e. a spectrum with equal energy per decade) and that the observed radiation results from the secondaries of pp collisions, they provided a fit to the Cos B γ -ray spectrum of 3C 273; to do so they used the radio data (representing the synchrotron emission by the same particles) to normalize the luminosity and invoked $\gamma - \gamma$ opacity to produce a good fit of the γ -ray spectrum and at the same time obtain an estimate of the radius of the emitting region. They also suggested [5] that spectra of similar form by all AGN could account for the diffuse γ -ray background.

Following these works, Kazanas & Ellison [6] proposed a dynamical model that could provide the required relativistic protons. In this model the relativistic protons are injected in by quasi-spherical shock in a volume of radius R , with the protons providing also the back pressure needed to support the shock. Steady state is achieved by the depletion of their pressure by nuclear collisions on time scale $\tau_{pp} =$

$1/n\sigma_{pp}c$, with the shock maintained at a radius $R \simeq v_{ff}\tau_{pp}$. This model is akin to the more recent ADAF models and, like them, it also involves only one free parameter, namely the normalized accretion rate \dot{m}/\dot{m}_E .

The AGN neutrino flux of this model can be easily estimated to be comparable to that of the observed photon flux and of spectrum similar to that of the protons. It would be proportionally smaller, of course, by the fraction of the photon luminosity contributed by a different process.

The issue of relativistic hadron loss scales, an issue of significance to time variability, was addressed at about the same time in [7]. These authors pointed out that at sufficiently high proton energies ($\gamma_p > 10^6$), photopion interactions rather than pp collisions dominate the energy loss of the relativistic protons. The reason is that for a general differential photon spectrum of the form $\epsilon^{-(\alpha+1)}$ ($\alpha \sim 1$), the number of photons above the threshold for photopion production, $\epsilon \sim m_\pi/\gamma_p$, becomes so large as γ_p increases that losses due to this process dominate those due to pp collisions. One can gauge the magnitude of this process by comparing the corresponding time scale with the light crossing time across the source region R/c . For comparison one can also provide the same ratio for the loss time scale of electrons with Lorentz factor $\gamma \gtrsim 1$. These ratios depend on the source compactness L/R and the cross section of the relevant interaction. They read

$$\frac{R/c}{t_{Th}} \sim \frac{L}{R} \frac{1}{m_e c^2} \frac{\sigma_T}{c} \quad (1)$$

$$\frac{R/c}{t_{p\gamma}} \sim \frac{L}{R} \frac{1}{m_{e,\pi} c^2} \frac{\sigma_{p\gamma} K_{e,\pi}}{c} \epsilon^{-\alpha} \quad (\alpha \sim 1) \quad (2)$$

where $K_{e,\pi}$ is the inelasticity of the reaction (either of the reaction $p\gamma \rightarrow p\pi$ or $p\gamma \rightarrow p e^+ e^-$) and $\sigma_{p\gamma}$ the associated cross section.

The authors of [7] derived also upper limits to the proton energy in AGN by comparing the acceleration and energy loss time. These are generally of order $\gamma_p \sim 10^8 - 10^{10}$, depending on the size and luminosity of the source, indicating that neutrinos of energies $E_\nu \sim 10^{16}$ eV could carry off roughly half of the bolometric photon luminosity. These estimates were thus quite favorable for the potential detection of neutrinos from AGN.

In addition to the neutrino fluxes from individual AGN, it was suggested in [8] that the diffuse neutrino flux from the entire AGN population may in fact be observable above that of the atmospheric neutrino background at energies $\gtrsim 10^5$ GeV. These authors assumed that the maximum proton energy in AGN is limited by the photopion losses on the observed average AGN spectrum; then they estimated the neutrino flux from the entire AGN population integrating over the AGN luminosity function as determined from X-ray observations. They estimated a flux of $\sim 2 \text{ yr}^{-1}$ upward events for the IMB detector and $20\text{-}200 \text{ yr}^{-1}$ for a DUMAND type detector for $E > 10^5$ GeV. They also noted that $n\gamma$ interactions could produce a significant number of $\bar{\nu}_e$'s at 6.3×10^{15} eV, the Glashow resonant energy for the

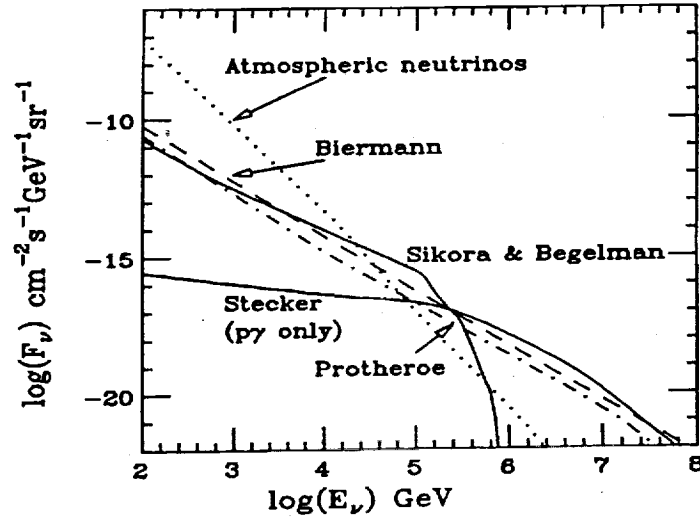


FIGURE 1. The diffuse AGN neutrino spectra according to refs.[8-11] along with the spectrum of atmospheric neutrinos.

reaction $\bar{\nu}_e e^- \rightarrow W^-$, which could lead to an enhanced reaction rate in a detector at these energies. Similar estimates with slightly different assumptions were also made by other groups (see e.g. [9], [10], [11]) with similar conclusions.

Figure 1 shows the diffuse AGN neutrino flux as computed by the set of the models discussed above along with the diffuse neutrino flux due to cosmic ray interactions in the atmosphere. The implicit assumption in these calculations is that the X-ray background is produced by the observed AGN and that *all* AGN which contribute to the diffuse X-ray background contain a non-thermal relativistic proton population extending to $10^{18} - 10^{20}$ eV depending on the source luminosity.

Besides neutrino production, the presence of relativistic protons in environments where hadronic collisions provide the main mode of proton energy conversion to radiation has additional effects which could be used to estimate the expected high energy neutrino emission. One such effect is the production of relativistic neutrons through the reactions $pp \rightarrow pn\pi^+$ and $p\gamma \rightarrow n\pi^+$. The neutron component behaves qualitatively very different from that of the proton because, due to their lack of charge, these particles escape ballistically from the production site. This property makes them ideal agents for the energy transport in high energy astrophysical sources [12,13]. The subsequent decay and re-conversion of neutrons into protons can then provide energy input into the local fluid much larger than its gravitational binding energy inducing outflows. The characteristic scale associated with the neutron lifetime, τ_n , namely $R_n \sim c\tau_n \simeq 3 \times 10^{13}$ cm, suggests that the escaping neutrons would convert into a relativistic fluid of protons in sources of size $R \gtrsim R_n$ [14]. Since relativistic outflows are observed in AGN it is worthwhile to consider their potential association with high energy neutrino emission.

At the same time, the production of relativistic electrons from the neutron decay at radii much larger than the region where the accretion luminosity would be converted into radiation by hadronic interactions, leads to emission thin to the $\gamma - \gamma$ and synchrotron self-absorption reactions; this lead to the suggestion that the radio loudness of AGN should be accompanied by γ -ray loudness and neutrino emission. Within this scenario then, radio quiet AGN would be those in which the relativistic neutrons are unable to escape their production region due to the high compactness of the source, thereby limiting the non-thermal emission to the vicinity of the compact object. Under this proposal, both radio loud and radio quiet AGN should be sources of high energy neutrinos, which could be potentially detectable.

Within this conceptual background concerning the dissipation of accretion energy in AGN (which provided the most favorable estimates for high energy neutrino emission), their broad band photon spectra were thought to result from the reprocessing of the primary power injected in the AGN "central engine" non-thermally at energies $E \gg 1$ MeV and its reprocessing to lower energies by the $\gamma\gamma \rightarrow e^+ e^-$ reaction (due to the high compactness of the sources this is the dominant reaction of high energy photons and electrons). The injected power eventually "escapes" at energies $E \lesssim m_e c^2$ producing by the inverse Compton process the observed high energy (X- and γ -ray) spectra of AGN. One of the generic conclusions of this line of thought was that the νF_ν (i.e. the luminosity per logarithmic energy interval) spectra of AGN should have a maximum at $E \sim m_e c^2$ with the X-ray slope being "flatter" the lower the compactness of the source. Because the details of the injection mechanism are lost in the reprocessing of the primary high energy radiation by successive generations of $e^+ e^-$ pairs, it was thought that the only way of determining the nature of the accelerator (i.e. whether it accelerates electrons directly or primarily protons) was through the detection or not of neutrino radiation.

2 *Post-CGRO Models*

The launch of CGRO opened up a new era in our understanding of the physics of AGN: First of all, it confirmed that AGN are indeed sources of high energy photons. Over sixty AGN were detected by the EGRET instrument aboard CGRO at energies in excess of 100 MeV and occasionally to energies $\simeq 10$ GeV, suggesting that these spectra are indeed non-thermal. At the same time, it was found that all the EGRET sources are associated with a particular class of AGN namely that of blazars. Blazars are AGN which are highly variable at all wavelengths with generally featureless spectra and which exhibit high polarization in optical and radio wavelengths. Blazars are a subset of the class of radio loud AGN (loosely speaking this means that their radio luminosity is roughly 10^{-3} of their bolometric one while in their radio quiet counterparts it is a much smaller fraction, typically 10^{-6}). The absence of any sign of $\gamma - \gamma$ absorption in the blazar γ -ray spectra despite their rapid variability, suggested that the γ -ray emitting plasma must be beamed toward the observer with Lorentz factors of order $\Gamma \sim 10$. It is generally

thought however, that the γ -ray emission results from inverse Compton scattering on electrons accelerated at shocks formed within the relativistically outflowing plasma.

At the same time, the OSSE instrument aboard CGRO which is sensitive to photons in the $\sim 50 - 2000$ keV range, showed that the radio quiet AGN spectra exhibit a cut-off roughly at an energy $E_\gamma \gtrsim 100$ keV. This indicated that the electron distributions responsible for the observed high energy radiation are for the most part thermal. There is no indication for significant emission at $\simeq 1$ MeV, as expected from non-thermal models. Figure 2 shows the OSSE spectrum of NGC 4151 given in [15]. This exhibits clearly a high energy cut-off as well as the upper limits of emission in the MeV region which give a measure of the maximum allowed non-thermal contribution. These spectra are consistent with inverse Compton scattering by thermal electrons and allow at most $\sim 10\%$ of the emitted power in non-thermal form.

There is also no indication of emission at higher energies (no radio quiet AGN has been detected by EGRET), as it would be expected if part of the radiation was produced by pp collisions; in that case the associated neutron production and escape could "dump" this energy at sufficiently large radii that the resulting γ -rays would not suffer much $\gamma - \gamma$ absorption. There is of course always the caveat that the escaping neutrons and the protons resulting from their decay convert most of their internal energy into bulk motion because of lack of the appropriate targets which would induce these particles to radiate. However, the limits of non-thermal emission tolerated by the data can also put a limit on the amount of a potential hadronic contribution and therefore to the amount of neutrinos expected from such objects. This can be, at best, no more than 10% of the amount estimated earlier, thus putting the diffuse neutrino emission at a level more than 10 times lower than estimated in [8-11].

In blazars, which do exhibit rather prominent non-thermal emission, it is generally thought that protons do not contribute significantly to the radiation process because of their long interaction time scales. Certainly they cannot contribute significantly through the pp reactions. However, Equation (2) shows that for sufficiently high values of the proton Lorentz factor ($\gamma_p \gtrsim 10^8$), the number of target photons which fulfill the photopion production threshold criterion can be sufficiently high to make possible the release of radiation at sufficiently short time scales to be consistent with the observed variability. These models are known as Proton Induced Cascade (PIC) models [16]. While these models cannot be refuted, they require that one pushes the acceleration of protons to its limits (Bohm limit, highest possible magnetic fields) [17]. Finally, an altogether different mechanism for converting the internal energy associated with a relativistic proton component is that of [18]. It is suggested there that the reflection of radiation produced by the outflowing plasma by matter located in the upstream region and its re-interception by the relativistically moving plasma can, under some not particularly stringent conditions, cause the release of a major fraction of the internal energy of the relativistic protons to $e^+ e^-$ pairs or $\pi^+ \pi^-$ on dynamical time scales. In this last case

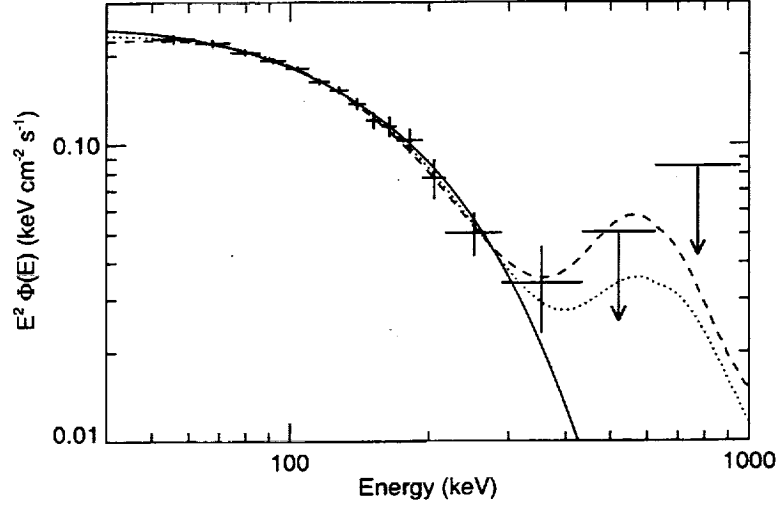


FIGURE 2. The spectrum of NGC 4151 as determined by OSSE and presented in Johnson et al (ref [15]). The solid curve is the fit with thermal Comptonization, the dotted one the best mix of thermal and non-thermal components while the dashed curve is the maximum allowed non-thermal contribution.

neutrino production is still possible in the AGN jets, with fluxes which now are not necessarily constant but correlate also with the observed γ -ray flares.

The most important conclusion of the CGRO observations concerning AGN may have been the delineation of two well defined classes previously known as Radio Loud and Radio Quiet and the tight correlation of these classes with the presence or not of high energy ($E_\gamma > 100$ MeV) γ -ray emission. Figure 3 shows the spectral energy distributions from radio to γ -rays of three objects of the first class (3C 279, 3C 273, Cen A) and one of the much more numerous class of Radio Quiet AGN (NGC 4151), as presented in [19]. The difference is quite apparent. The difference in the γ -ray spectra of the first two objects from that of Cen A can be attributed to the fact that the relativistic outflows which boost the γ -ray emission in these objects point toward the observer, while the jet associated with Cen A is known to be almost on the plane of the sky. Nonetheless, the > 50 keV spectra of Cen A and NGC 4151 are quite different, with the latter indicating a cut-off above 50 keV while the former is a power law, which is now known to extend to the EGRET energy range (100 MeV). These spectra, then, argue rather convincingly for the absence of a significant non-thermal component in radio quiet AGN, whether hadronic or

not. The issue with the radio loud AGN is not as clear cut, because of the apparent presence of non-thermal particle populations as manifest by the observed spectra.

III CONCLUSIONS, DISCUSSION

After much speculation and modeling of the neutrino emission from AGN, the γ -ray observations of the past decade have rather conclusively, in my view, shown that the majority of AGN, namely the radio quiet ones, do not exhibit signs of significant non-thermal emission (if any) whether hadronic or not, and as such they should not be expected to be sources of high energy ($E_\nu \gtrsim 1$ TeV) neutrinos. The diffuse high energy neutrino flux should be then revised accordingly; in refs. [8–11] it had been normalized to that of the diffuse X-ray background, with the assumption that the latter receives a major contribution from AGN. While AGN may still be the major contributors to the diffuse X-ray background the ratio of their neutrino-to-X-ray fluxes seems to be much smaller than assumed in the above references.

One should still bear in mind, though, that proton acceleration in accretion flows and their subsequent escape is still a possibility [20]. However, the conversion of the energy of this accelerated proton component into radiation (photons) and neutrinos is not likely to be very efficient. The only component in the spectra of radio quiet AGN which could possibly have its origin in this process is their radio emission. However, this is much lower than their bolometric luminosity by a large factor ($\sim 10^6$), thus making any potential neutrino emission practically insignificant.

Radio Loud AGN present a much better case as potential sources of high energy neutrinos. Even though the majority view is currently that the observed non-thermal emission is due to acceleration of electrons, as discussed above, hadronic interactions may also be involved in the production of the observed high energy radiation. Of particular interest are the γ -ray detections of a number of nearby blazars at energies $E_\gamma \sim 1 - 10$ TeV which indicate that, if they result from hadronic interactions, there should also be accompanied by neutrino emission of similar energy and flux; if this is indeed the case, then they could be potentially observable.

In conclusion, high energy neutrino emission from AGN does not appear as compelling as once thought to be. In radio quiet AGN in particular, which comprise roughly 90% of the AGN population, there appears to be very little non-thermal activity in general, let alone in relativistic hadrons. This fact is rather puzzling, because the observed prominent X-ray emission suggests the presence of tenuous, hot plasmas. Even if most of the particles of these plasmas are indeed in a thermal distribution, the presence of turbulent magnetic fields within the X-ray emitting gas and their annihilation should put a significant fraction of the available power into an accelerated hadron component; after all, such a process is known to take place in solar flares which are presumably powered by a similar mechanism. For some not totally obvious reason, this proton energization does not seem to take

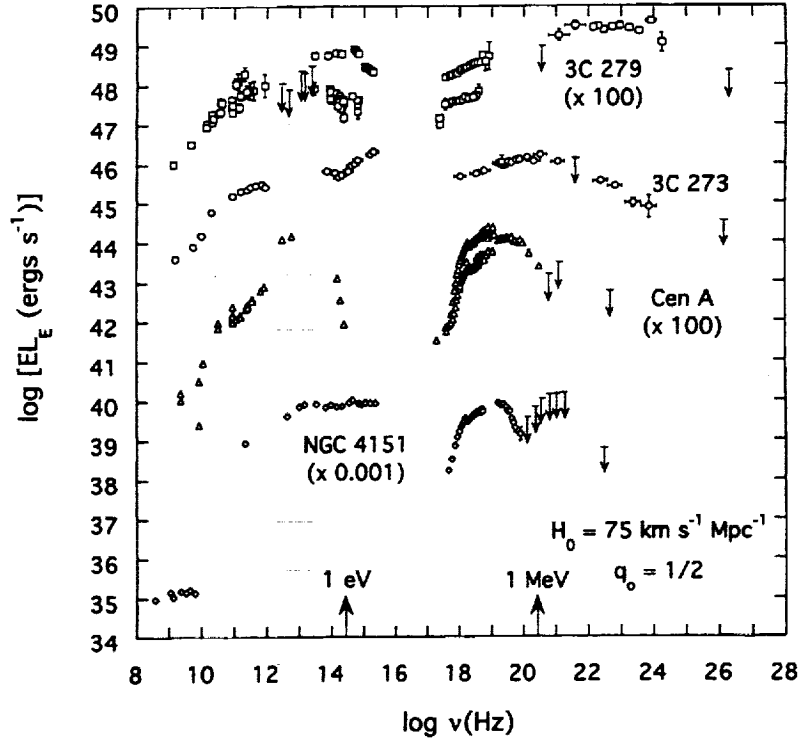


FIGURE 3. The spectral energy distribution in the two AGN classes as given in Dermer & Gehrels (1995).

place in AGN.

Radio loud AGN do offer a more promising source of high energy neutrinos. However, as of now, there has not been an unequivocal sign indicating that relativistic hadrons are indeed involved in the emission. However, these cannot be excluded and the arguments against their presence, based on their long radiative timescales can, to some extent, be circumvented by invoking either PICs [16] or the process suggested in [18]. On the other hand, relativistic hadrons, because of their very long energy loss time scales, are ideal for producing the acceleration of the outflowing plasma and for transporting energy far from the compact object where the γ -ray emission apparently takes place. Precisely for these reasons their presence is invoked at will in GRBs [21]. Their presence, and the accompanying neutrino emission in AGN, then, should not be considered as too unreasonable an assumption.

Eventually the issue of high energy neutrinos from AGN or other astrophysical sites will be settled only observationally. We hope that AMANDA and its successor, NESTOR or ANTARES will be full of surprises!

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